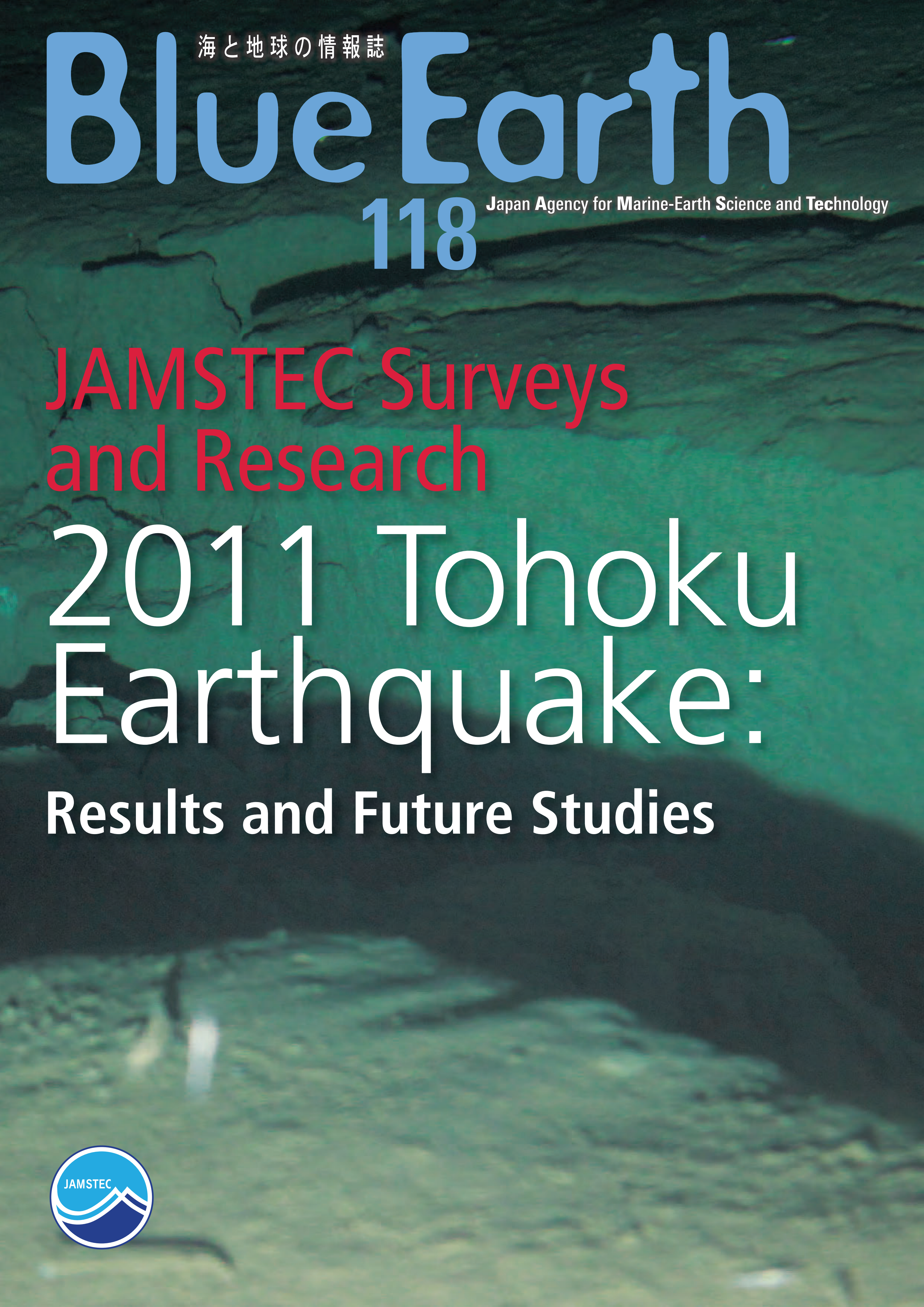


海と地球の情報誌

Blue Earth

118

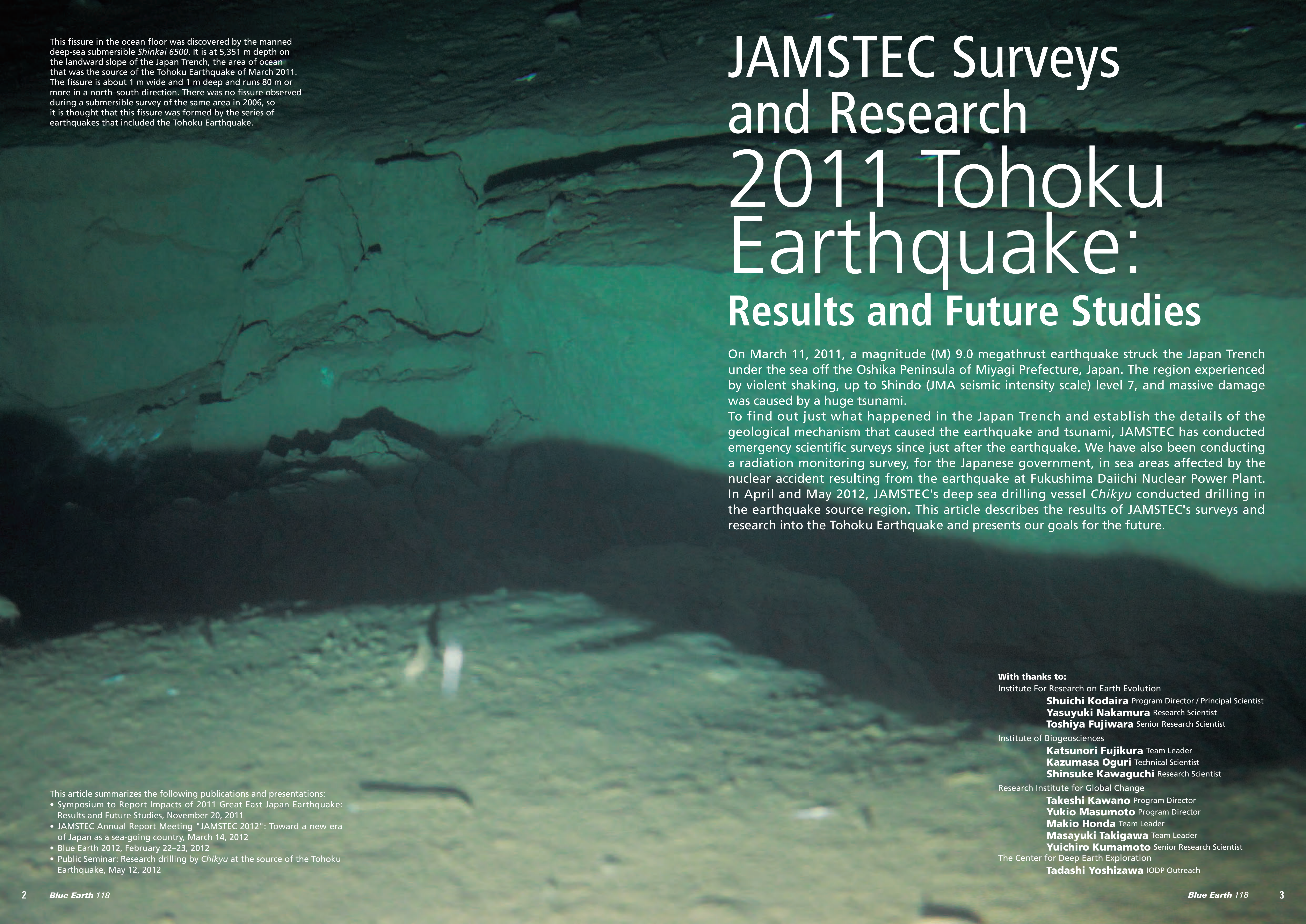
Japan Agency for Marine-Earth Science and Technology

JAMSTEC Surveys and Research

2011 Tohoku Earthquake:

Results and Future Studies

JAMSTEC



This fissure in the ocean floor was discovered by the manned deep-sea submersible *Shinkai 6500*. It is at 5,351 m depth on the landward slope of the Japan Trench, the area of ocean that was the source of the Tohoku Earthquake of March 2011. The fissure is about 1 m wide and 1 m deep and runs 80 m or more in a north–south direction. There was no fissure observed during a submersible survey of the same area in 2006, so it is thought that this fissure was formed by the series of earthquakes that included the Tohoku Earthquake.

JAMSTEC Surveys and Research 2011 Tohoku Earthquake:

Results and Future Studies

On March 11, 2011, a magnitude (M) 9.0 megathrust earthquake struck the Japan Trench under the sea off the Oshika Peninsula of Miyagi Prefecture, Japan. The region experienced by violent shaking, up to Shindo (JMA seismic intensity scale) level 7, and massive damage was caused by a huge tsunami.

To find out just what happened in the Japan Trench and establish the details of the geological mechanism that caused the earthquake and tsunami, JAMSTEC has conducted emergency scientific surveys since just after the earthquake. We have also been conducting a radiation monitoring survey, for the Japanese government, in sea areas affected by the nuclear accident resulting from the earthquake at Fukushima Daiichi Nuclear Power Plant. In April and May 2012, JAMSTEC's deep sea drilling vessel *Chikyu* conducted drilling in the earthquake source region. This article describes the results of JAMSTEC's surveys and research into the Tohoku Earthquake and presents our goals for the future.

This article summarizes the following publications and presentations:

- Symposium to Report Impacts of 2011 Great East Japan Earthquake: Results and Future Studies, November 20, 2011
- JAMSTEC Annual Report Meeting "JAMSTEC 2012": Toward a new era of Japan as a sea-going country, March 14, 2012
- Blue Earth 2012, February 22–23, 2012
- Public Seminar: Research drilling by *Chikyu* at the source of the Tohoku Earthquake, May 12, 2012

With thanks to:
Institute For Research on Earth Evolution
Shuichi Kodaira Program Director / Principal Scientist
Yasuyuki Nakamura Research Scientist
Toshiya Fujiwara Senior Research Scientist
Institute of Biogeosciences
Katsunori Fujikura Team Leader
Kazumasa Oguri Technical Scientist
Shinsuke Kawaguchi Research Scientist
Research Institute for Global Change
Takeshi Kawano Program Director
Yukio Masumoto Program Director
Makio Honda Team Leader
Masayuki Takigawa Team Leader
Yuichiro Kumamoto Senior Research Scientist
The Center for Deep Earth Exploration
Tadashi Yoshizawa IODP Outreach

JAMSTEC's Activities: Rapid response Scientific Surveys, Ocean Radiation Monitoring, and Drilling into the Earthquake fault zone

After the Tohoku Earthquake at 2:46 p.m. on March 11, 2011, the response of most seismologists was that the subduction zone earthquake model that we have been using cannot explain this earthquake.

The hypocenter of the earthquake was 24 km below the seafloor 130 km east-southeast of Oshika Peninsula, Miyagi, and the magnitude of the earthquake was a huge M9.0. Strong tremors of JMA seismic intensity scale 5 and above were experienced over a wide area of East Japan, with shaking of up to Shindo 7 being recorded in Kurihara City, Miyagi. The tsunami caused by the earthquake reached heights of 40 m and caused colossal damage to the coastline of the Tohoku and Kanto regions. These disasters are referred to as the 2011 Tohoku Earthquake and Tsunami. In the aftermath of the earthquake, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) was a hive of activity as we began preparations for Rapid response scientific surveys.

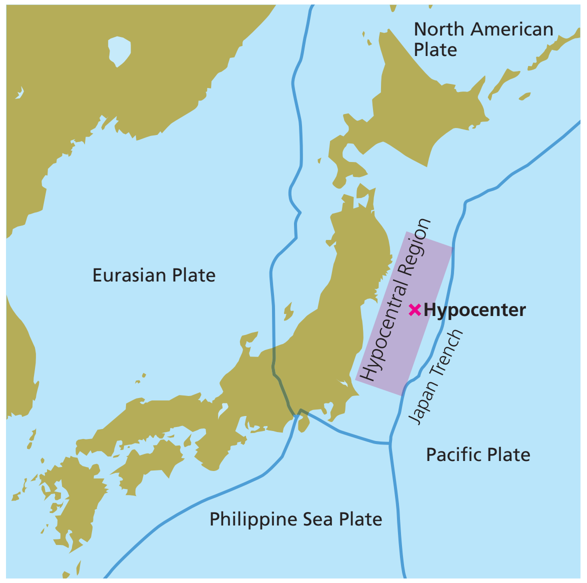
An earthquake happens when a fault slips. The Tohoku Earthquake was caused by a slip at the boundary between the North American Plate, on which northeast Japan sits, and the Pacific Plate, which is sliding (subducting) beneath the North American plate. When a plate that is moving in an earthquake lifts up the ocean water, a tsunami sometimes occurs. This type of earthquake is referred to as a subduction zone earthquake or as an interplate earthquake. Many subduction zone earthquakes have occurred along the line of the Japan Trench where the Pacific Plate is subducting beneath the North American Plate, and more earthquakes were expected to happen in the near future. However, the magnitude of any such earthquake was not expected exceed M8.0. So why was there a M9.0 megathrust earthquake with a tsunami as high as 40 m? To identify the mechanism that caused this, it is necessary to study questions such as changes in structure at and below the seafloor. JAMSTEC has the ships, equipment and people to do this. Our mission was to find out the facts of the earthquake, tell the world of our findings, and pass them on to future generations. With this inspiration, we started our scientific surveys just three days after the earthquake.

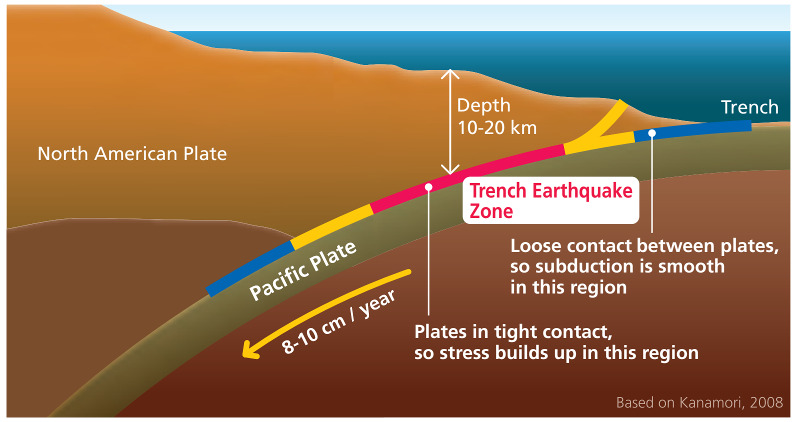
The scientific surveys had three major aspects: a survey of the topography of the seafloor and of geological structure under the seafloor, carried out by the deep sea research vessel *Kairei* and the research vessel *Kaiyo*; a seafloor surface survey using the deep ocean floor survey system Deep Tow and the manned research submersible *Shinkai 6500*; and a general survey including water samples and bottom samples from the earthquake source region by the oceanographic research vessel *Mirai* and the research vessels *Hakuho Maru* and *Tansei Maru*.

After the accident at Fukushima Daiichi Nuclear Power Plant resulting from the earthquake and tsunami, at the request of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), JAMSTEC also conducted a radiation monitoring survey in nearby sea areas from March 22, using the vessels *Hakuho Maru*, *Mirai*, *Kairei*, *Yokosuka*, *Natsushima* and *Kaiyo*.

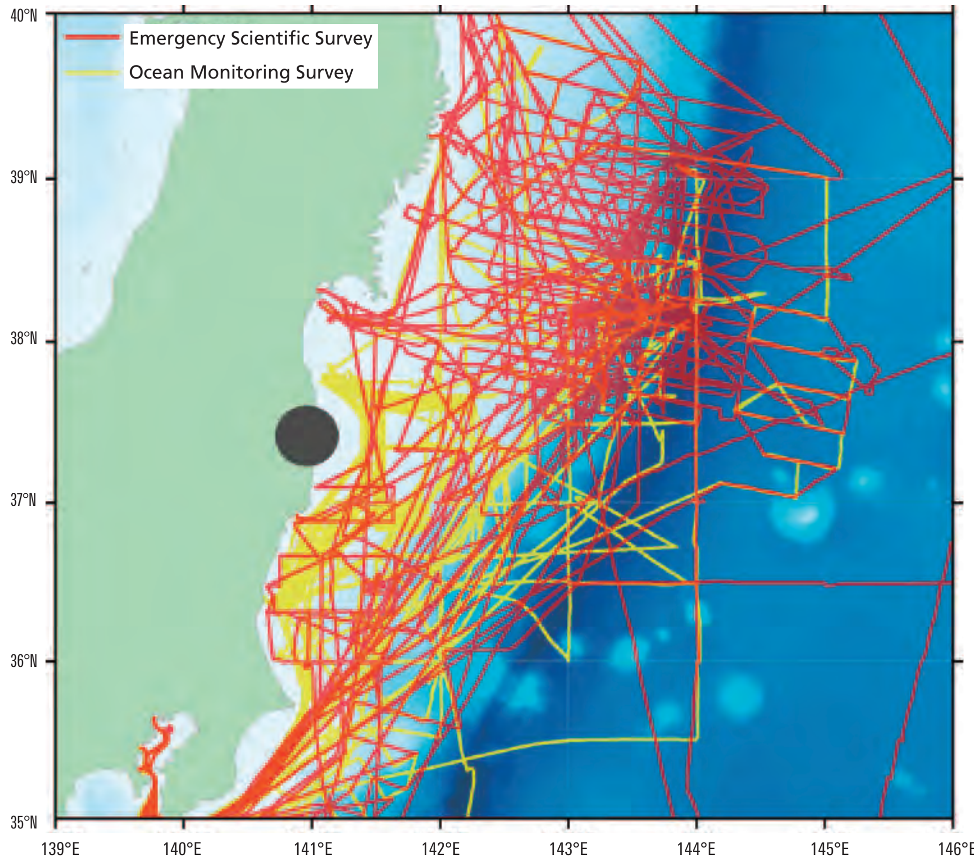
As of May 12, 2012, the Rapid response scientific surveys and monitoring survey had been going for 525 days and had involved 33 vessels. The surveys are still continuing. From April 1 to May 24, 2012, on Expedition 343 of the Integrated Ocean Drilling Program (IODP), the deep sea drilling vessel *Chikyu* conducted drilling in the earthquake source region. From these surveys and research, the facts of the Tohoku Earthquake have gradually become clearer.

Tectonic plates around Japan and the source region of the Tohoku Earthquake
The Earth's surface is covered with some dozen plates of rock called tectonic plates. The edges of four of these plates meet and collide together around Japan. The Tohoku Earthquake was a trench earthquake which occurred at the boundary between the North American Plate, on which northeast Japan sits, and the Pacific Plate, which is subducting beneath the North American Plate. From measurements of seismic waves and the tsunami, we believe that a fault at the boundary between the plates slipped throughout an area 500 km north-to-south, from the Sanriku coast to Ibaraki Prefecture, and 200 km east-to-west.





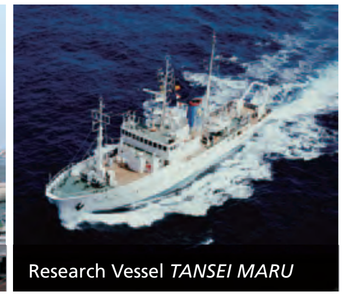
The mechanism of trench earthquakes as previously understood
Previously it was thought that the plates are in tight contact with one another at depths of 10–20 km, so the subducting Pacific Plate drags down the North American Plate and stress builds up at the plate boundary. When the stress becomes too great, the plate boundary suddenly buckles off and the plates slip against one another: this is a trench earthquake. Where the plate boundary is closer to the surface, near the trench, the plates are loosely fitted together and slide smoothly, so it was thought there was not much slippage when an earthquake happens.



Tracks of ships on the emergency scientific survey and the ocean monitoring survey
As of May 12, 2012, the emergency scientific survey and ocean monitoring survey had been in progress for 525 days and the number of vessels involved was up to 33. The black circle shows the 20 km exclusion zone around Fukushima Daiichi Nuclear Power Plant. Below are some of the ships involved in the survey and their research activities.

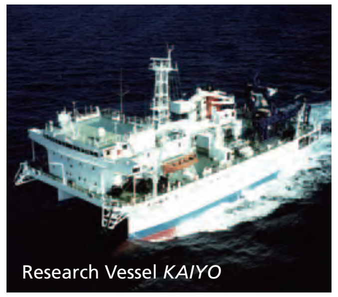

Deep Sea Research Vessel *KAIREI*

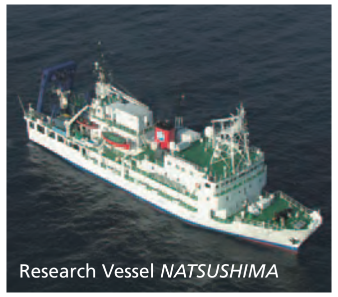

Research Vessel *HAKUHO MARU*


Research Vessel *TANSEI MARU*


Support Vessel *YOKOSUKA*


Manned Research Submersible *SHINKAI 6500*


Research Vessel *KAIYO*


Research Vessel *NATSUSHIMA*


Oceanographic Research Vessel *MIRAI*


Deep Sea Drilling Vessel *CHIKYU*

Major activities by JAMSTEC since the Tohoku Earthquake

March 14 to March 31, 2011
Japan Trench area
Measurement of aftershocks by using ocean bottom seismographs and survey of crustal structure by using multi-channel seismic reflection survey system by the *Karei*

March 22 to July 17, 2011
Off Fukushima
Radiation monitoring with the *Hakuho Maru*, *Mirai*, *Kairei*, *Yokosuka* and *Natsushima* working in shifts

April 28 to May 21, 2011
Japan Trench area
Measurement of aftershocks by using ocean bottom seismographs and survey of crustal structure by using multi-channel seismic reflection survey system by the *Karei*

June 3 to 23, 2011
Off Sanriku
Surveys of topography and geology and sampling of seawater, sediment, etc. by the *Yokosuka*

July 11 to 28, 2011
Off Sanriku
Surveys of topography and geology and sampling of seawater, sediment, etc. by the *Yokosuka*

July 30 to August 14, 2011
Off Sanriku
Surveys of topography and geology and sampling of deep-sea organisms, seawater, sediment, etc. by the *Yokosuka* and *Shinkai 6500*

August 22 to 28, 2011
Off Fukushima
Radiation monitoring by the *Kaiyo*

August 27 to September 11, 2011 (and other dates)
Japan Trench area
Measurement of aftershocks using ocean bottom seismographs and survey of crustal structure by using multi-channel seismic reflection survey system by the *Karei*

October 21 to November 11, 2011
Japan Trench area
Recovery of ocean bottom seismographs and survey of crustal structure by using multi-channel seismic reflection survey system by the *Kaiyo*

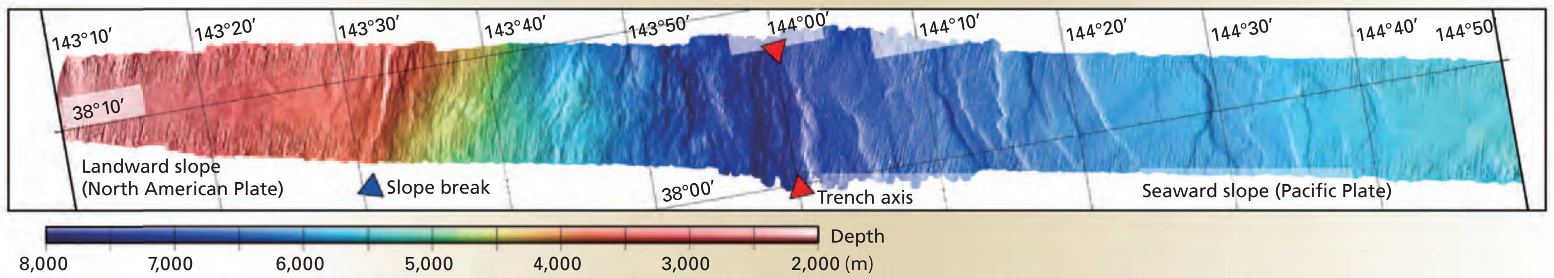
November 30 to December 2, 2011
Off Fukushima
Radiation monitoring by the *Kaiyo*, and various surveys and measurements including water and bottom sampling by the *Mirai*, *Hakuho Maru* and *Tansei Maru*

February 20 to March 3, 2012
Off Sanriku
Surveys and measurements in the Japan Trench area by the *Mirai*

March 6 to 30, 2012
Off Sanriku
Surveys and measurements in coastal areas by the *Mirai*

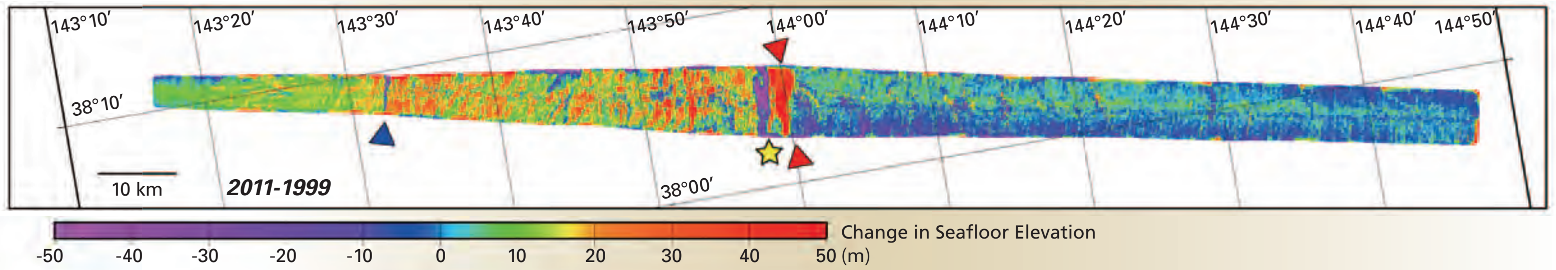
April 1 to May 24, 2012
Off Sanriku
Survey drilling in source area of the Tohoku Earthquake by the *Chikyu*

The Landward Side Seafloor Moved 50 m East-southeast and 7–10 m Upward, Causing the Huge Tsunami



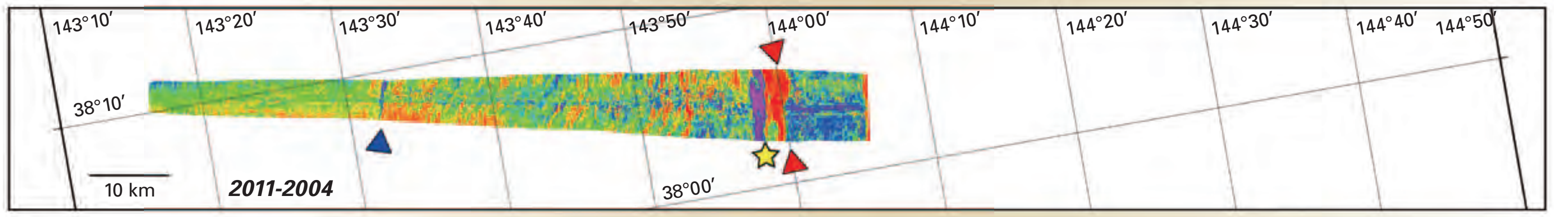
Seafloor topography in 2011

The water depth is shown by colors, red being shallower and blue deeper. The red triangles show the position of the trench axis. The blue triangle shows the position of a slope transition on the landward slope, the boundary where the slope changes steeper down to the trench axis.



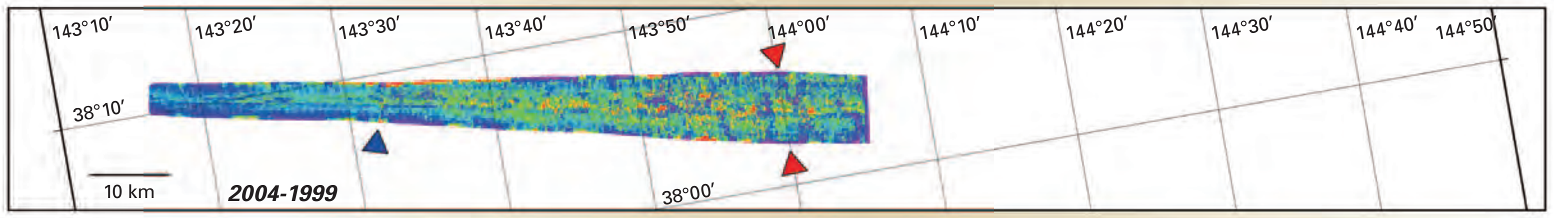
Changes in topography between 1999 and 2011

The colors show changes in depth, with red showing uplift of the seafloor and purple showing subsidence of the seafloor. On the landward slope, the seafloor from the slope transition to the trench axis uplifted greatly. We estimated that this area moved about 56 m to east-southeast and 10 m upward. Close to the trench axis, there are areas that collapsed by around 50 m and rose by around 50 m (marked with the star). We think this is due to landslides caused by the earthquake and changes in sub-seafloor structure. The area shown in this map is smaller than that in the seafloor topography in 2011, as only areas accurately measured are shown.



Changes in topography between 2004 and 2011

This map shows generally the same changes as the comparison between 1999 and 2011. The seafloor of the landward slope from the slope transition to the trench axis uplifted by a lot. There are small differences in the numbers because of differences in the data used, but we estimated a shift of 50 m to east-southeast and 7 m upward.



Changes in topography between 1999 and 2004

Only variations of a few meters can be seen. There were no significant changes in the seafloor topography.

From Fujiwara et al. (2011)

The first ship to embark on the scientific survey was the R/V (Research Vessel) *Kairei*. R/V *Kairei* is equipped with a multi-narrow beam sounding instrument for seafloor topography surveys and a multi-channel reflection seismic survey system for sub-seafloor structure surveys'. When the Tohoku Earthquake happened, R/V *Kairei* was conducting a survey in the Ogasawara area south of Japan. R/V *Kairei* suspended this survey and returned to JAMSTEC headquarters in Yokosuka. After preparations, R/V *Kairei* set out for the earthquake source area.

One of R/V *Kairei*'s tasks was to survey the seafloor topography with the multi-narrow beam sounding instrument and identify how the seafloor topography was changed by the earthquake. Sound waves are transmitted from the bottom of the ship in a fan shape, are reflected from the seafloor, and return to the ship. The travel time of the sound waves to return shows sea depths in the survey area, and thus the seafloor topography. Seafloor topography surveys have been conducted in the Japan Trench area several times before. By comparing the measurements with previous measurements along the same survey tracks, changes caused by the earthquake can be identified. The first focus was the track of the surveys in 1999 and 2004. This line crosses the trench between the Pacific Plate and the North American Plate, and is close to the source of the earthquake.

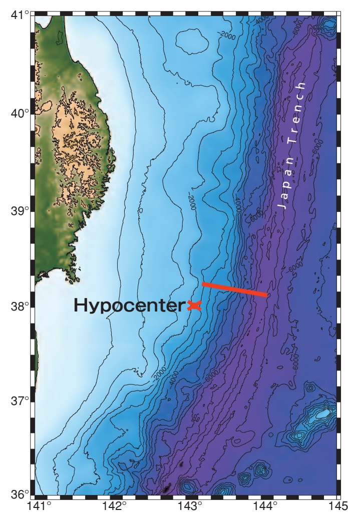
In the seafloor topography map obtained from the 2011 survey, the deepest part is the trench axis (indicated by the red triangles in the left figures), where one plate slides under the other. There are slopes on both sides of the trench axis, which are referred to as the seaward slope and the landward slope. The landward slope has a steep gradient from a slope transition (indicated by the blue triangle in the left figure) down to the trench axis. These features are the same as in the seafloor topography found by the surveys of 1999 and 2004.

If we calculate differences between the topography of 2011 after the earthquake and the topography of 1999 before the earthquake, clear changes in height can be seen. There is a big difference between the seaward and the landward sides of the trench axis: the seafloor has risen on the landward side, particularly the landward slope from the slope transition to the trench axis. The same difference can be seen in a comparison between 2011 and 2004. If differences between the topography of 2004 and the topography of 1999 are calculated, there were almost no changes in height, which indicates that the changes were caused by the Tohoku Earthquake.

From this analysis, we estimate that the seafloor topography was shifted about 50 m east-southeast and 7–10 m upward by the earthquake. This result could be obtained only because we had records from previous surveys. Surveys of seafloor topography were conducted off Sumatra, Indonesia after the M9.1 subduction zone earthquake that struck there in 2004, but because there had been no previous surveys, changes could not be identified. This is an example of how, although basic survey research may not be immediately useful, it can subsequently become very important.

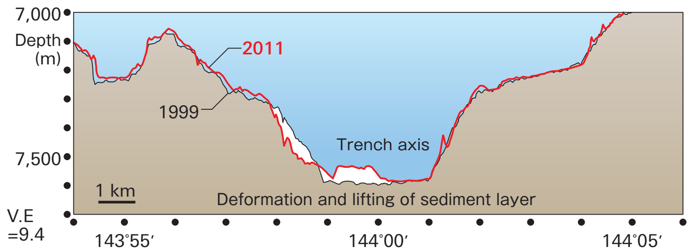
When the seafloor rose, the seawater above was lifted up, causing the tsunami. But how could this change in topography cause such a big tsunami? We think that the rise of 7–10 m of the seafloor in the earthquake and a slope effect combined to create the huge tsunami. The landward side slope is higher and the slope is particularly steep close to the trench axis. Because this slope shifted horizontally toward the trench axis, the ocean surface was lifted up by more than the vertical rise of the seafloor. The waves of the tsunami that were measured on that day can be understood using a simulation of a tsunami being caused by this change in topography.

This analysis of the changes in topography gave one more important result: that the changes reached as far as the trench axis. This means that the fault at the plate boundary was slipping all the way up to the trench axis. A slip associated with a subduction zone earthquake has never before been observed to reach a trench axis, and most seismologists did not think that it could happen. So what happened below the seafloor? The facts were uncovered by JAMSTEC's emergency scientific survey.



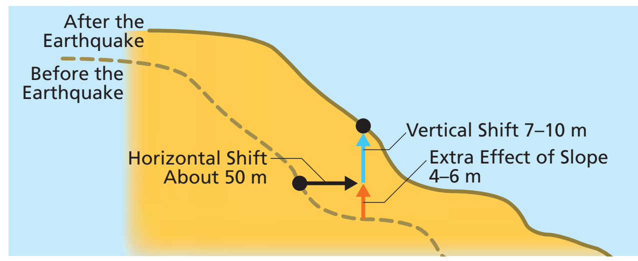
Survey track of seafloor topography survey

The red line shows the survey track of the seafloor topography survey. The red cross shows the epicenter of the mainshock of the Tohoku Earthquake.



Topography changes near trench axis

The slope at the landward side of the trench axis collapsed over a range of 1 km when the earthquake happened. The floor of the trench axis rose by about 50 m over about 1.5 km width.



The change in seafloor topography and the effect of the slope

The actual uplift of the seafloor was 7–10 m. However, the slope also shifted about 50 m horizontally, producing an effect equivalent to additional uplift of 4–6 m. As a result, the ocean surface was lifted up 11–16 m, causing the huge tsunami.

The First Observations of a subduction zone Earthquake Fault and Changes to Underground Structures Caused by the Earthquake

The general understanding of subduction zone earthquakes has been that the zone in which earthquakes occur—in which an over-stressed plate boundary ruptures and suddenly slips by a large amount—is 10 to 20 km below the seafloor. In a shallow zone close to a trench axis, the plates are in loose contact with one another and subduction is smooth, so stress does not build up and there is not a large amount of slipping when an earthquake happens. However, the changes in the seafloor topography discovered by JAMSTEC's scientific survey show that the fault at the plate boundary slipped all the way up to the trench axis in the Tohoku Earthquake. This event cannot be explained by the conventional mechanism for subduction zone earthquakes.

So what kind of fault and what kind of slipping could have reached the trench axis? To answer this question, a reflection seismic survey is useful. Tiny seismic waves are sent out from air guns and sound waves that bounce back from geological layers and faults are measured, revealing the structure below the seafloor. The sub-seafloor structure under the Japan Trench had been previously studied by a reflection seismic survey, but the survey tracks were spaced apart by distances of 50 to 100 km. After the earthquake, we carried out a reflection seismic survey along 14 survey tracks crossing the trench axis and two survey tracks parallel to the trench axis. These survey tracks were spaced apart by 10 to 20 km and showed sub-seafloor structures in detail, such as differences between north and south in the structures under the landward slope.

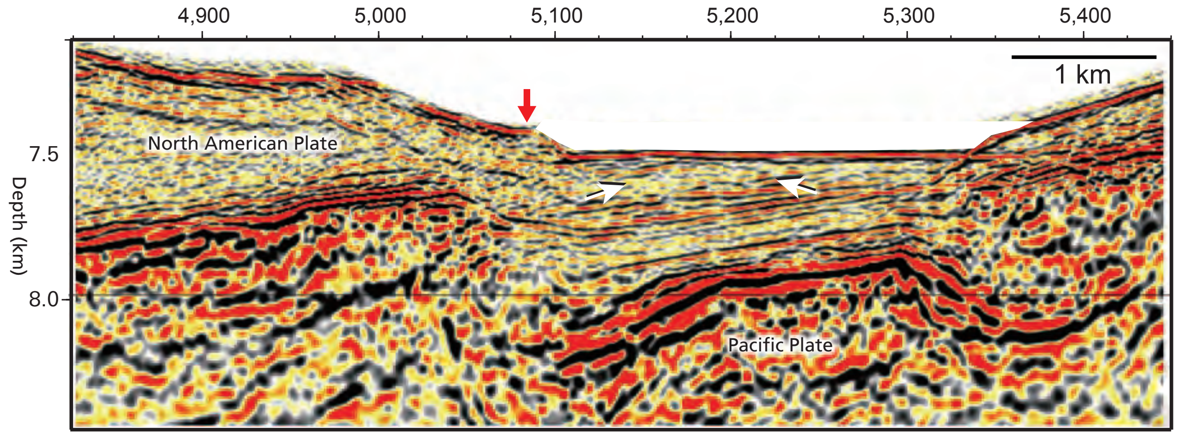
What we most needed to see was the sub-seafloor structures at the ends of the fault and near the trench axis. We magnified data from the vicinity of the trench axis and compared the structure observed in 2011, after the earthquake, with that observed in 1999, before the earthquake. Thick dark red and black lines can be seen in the right figures, which is the upper surface of the Pacific Plate. In the 1999 data, there are layers of sediment on top of the Pacific Plate and the seafloor is flat at the trench axis. Note the small rise on the seaward side of the trench axis. In the 2011 data, this rise has shifted toward the ocean side and the seafloor that was flat has bulged upward. There are many reverse faults in the sediment layer, which are caused by compression forces. These changes can only have been caused by the Tohoku Earthquake.

From a detailed analysis of the sub-seafloor structure data, the nature of the earthquake becomes apparent: slippage of the fault started about 24 km below the seafloor and progressed to the trench axis along the upper face of a layer of sediment eroded from the bottom of the North American Plate, about 200 m above the top face of the Pacific Plate. The fault branched into a number of faults that broke through to the seafloor.

This is the first time that the fault of a subduction zone earthquake and structural changes caused by the quake have been observed. These deformations of structure can be considered as a record of the megathrust earthquake. By studying where in the Japan Trench similar structural deformations have occurred, we can learn how earthquakes of the same type as the Tohoku Earthquake have happened. To this end, we are planning a sub-seafloor structural survey of the whole of the Japan Trench with a higher level of resolution than before.

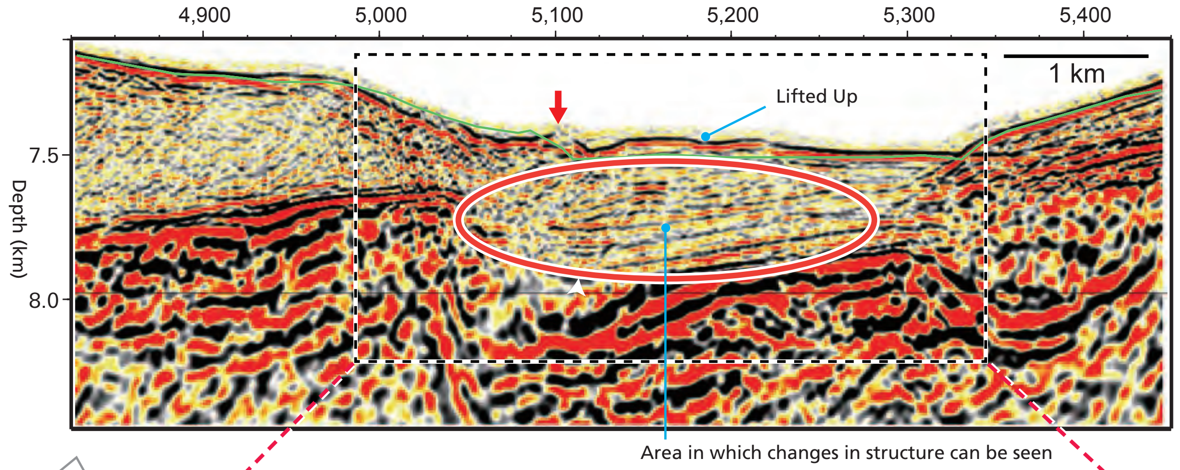
However, we have not found the answer as to why the fault slipped as far as the trench axis. It could be that, contrary to previous understanding, the plates are in strong contact with one another near the trench axis. To understand the mechanism of the Tohoku Earthquake, we need to learn about the characteristics of the fault and how tightly the plates fit together. The only way to do this is by directly examining the characteristics of the fault and surrounding area by drilling into the seafloor.

In October 2011, R/V *Kaiyo* conducted a high-resolution reflection seismic survey near the trench axis and drilling sites were determined. D/V *Chikyu* conducted drilling in April and May 2012.

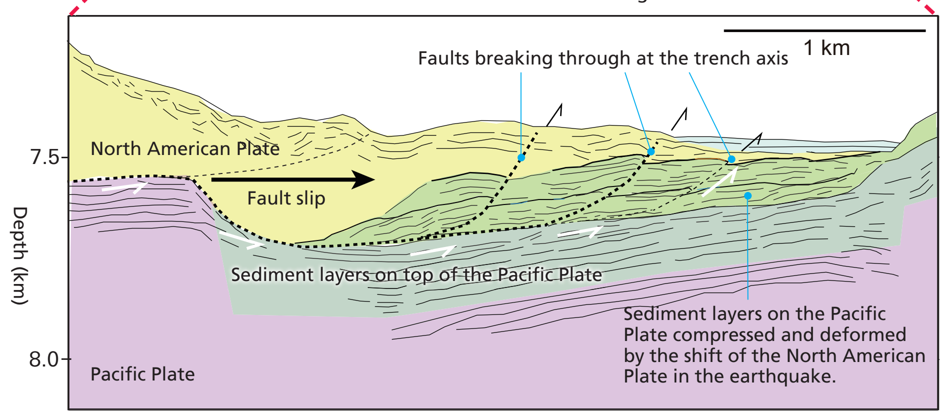


Changes in sub-seafloor structure near the trench axis caused by the earthquake

1999
The seafloor is flat at the trench axis and there are sediment layers over the Pacific Plate. There is a small rise (red arrow) at the landward side of the trench.



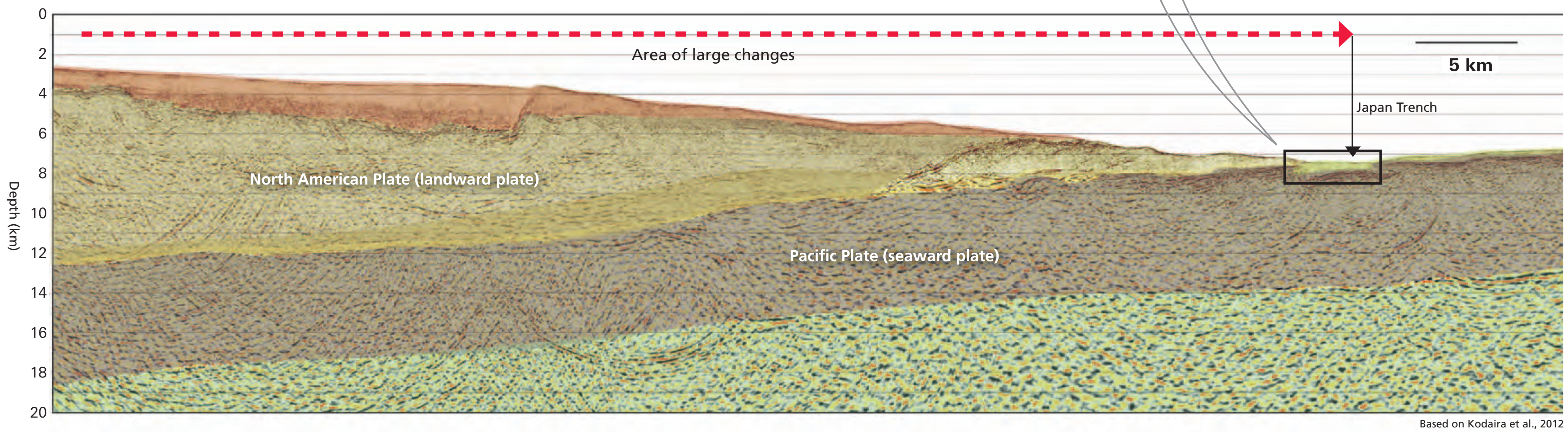
2011
The rise (red arrow) at the landward side of the trench has moved toward the trench axis, and the previously flat seafloor of the trench has been lifted up. The green line shows where the seafloor was in 1999. The sediment has been compressed and deformed by the movement of the landward plate 50 m east-southeast; many reverse faults can be seen.



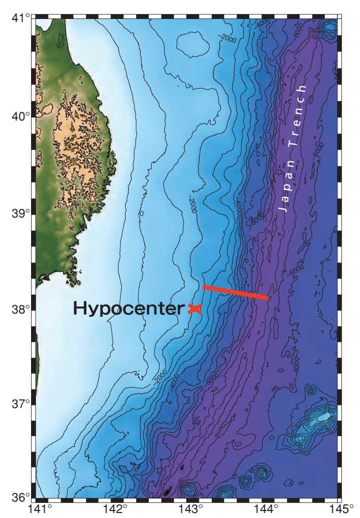
Based on Kodaira et al., 2012

Faults slipping in the Tohoku Earthquake
The fault slip began about 24 km below the sea surface and plate boundary ruptured. When the fault slip reached the trench axis, it compressed and deformed the sediments, and branched into several faults which broke through to the surface.

Seismic section of sub-seafloor structure in the earthquake source area, from the 2011 seismic reflection survey
Seismic waves are strongly reflected by faults and geological layers. The top face of the Pacific Plate subducting under the North American Plate can be clearly seen. The North American Plate has many normal faults, which are faults caused by the rock being stretched. The emergency scientific survey showed that there are more normal faults in the Japan Trench off Miyagi-Iwate boundary area.

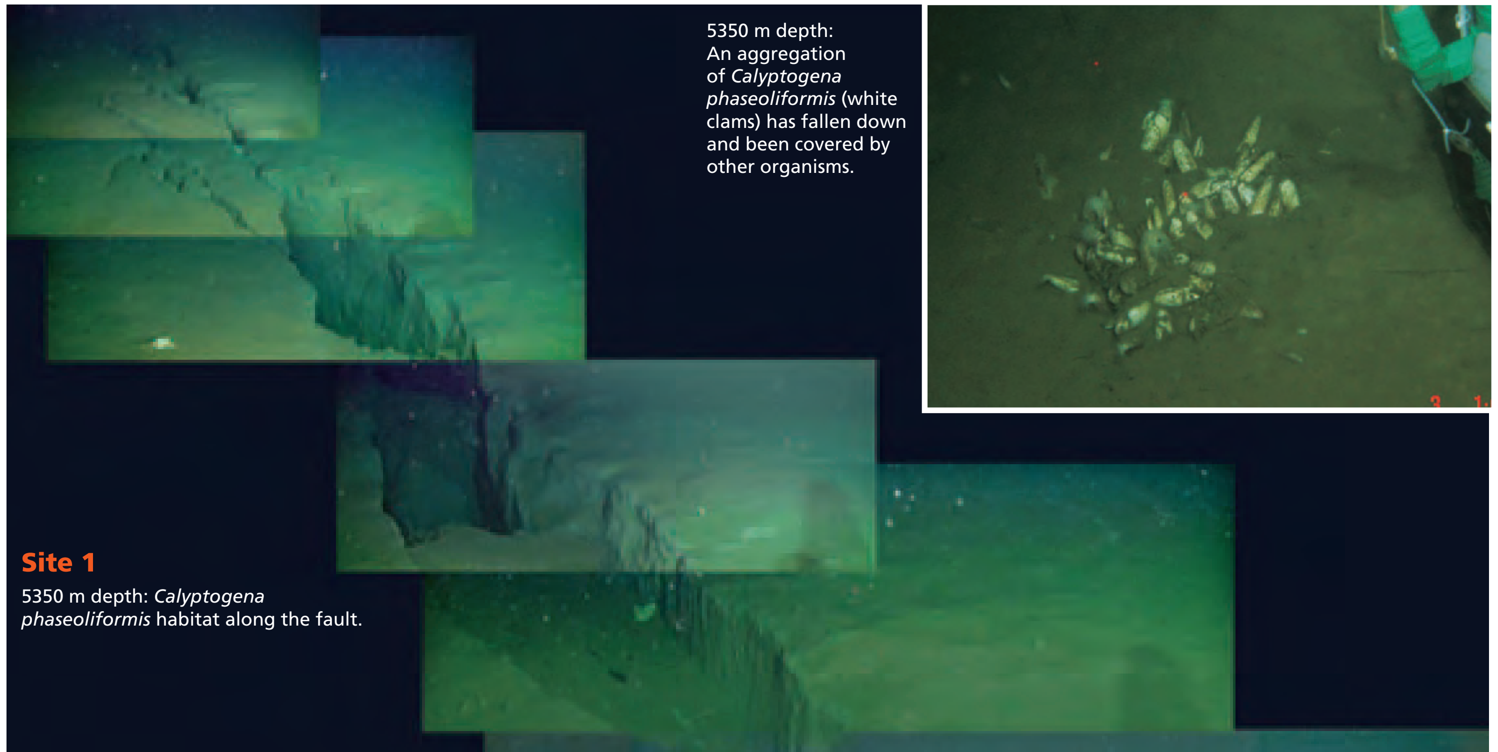


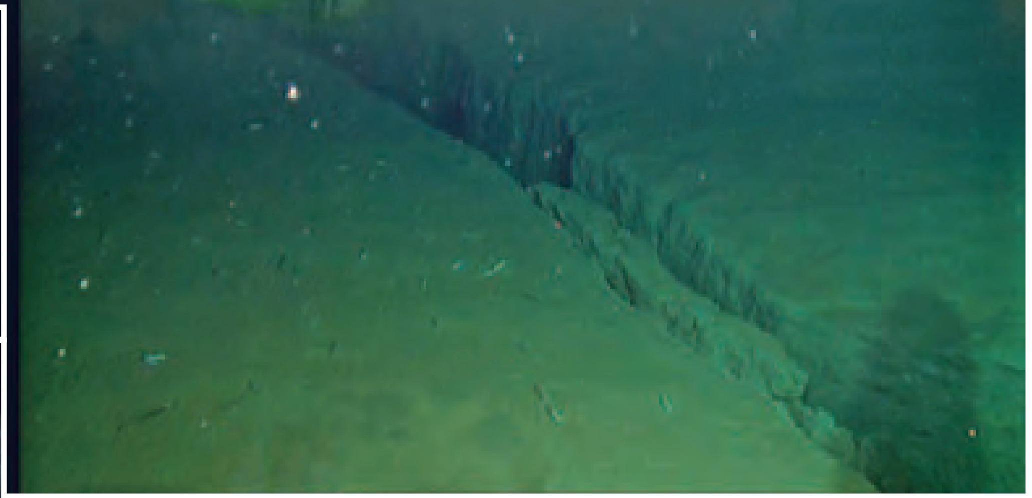
Based on Kodaira et al., 2012



Survey track of the seismic reflection survey
The survey follows the same line as the seafloor topography survey described on page 6. This survey track was also used in the 1999 seismic reflection survey.

What *Shinkai 6500* found at the Deep-sea Bottom: Fissures in the Seafloor, Bacterial Mats, and Aggregations of Sea Cucumbers



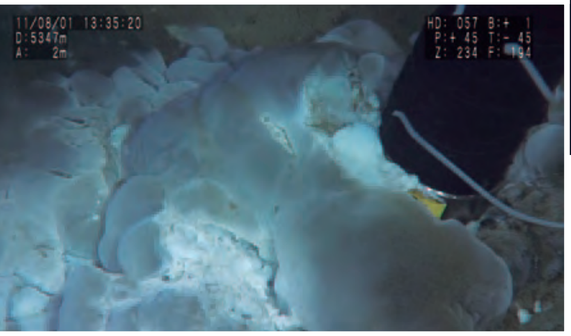


5350 m depth: An aggregation of *Calyptogena phaseoliformis* (white clams) has fallen down and been covered by other organisms.

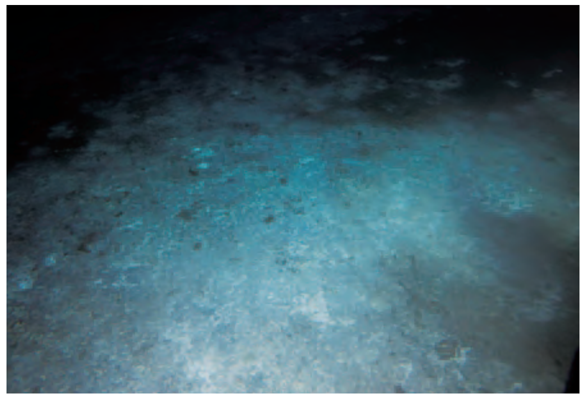
Site 1

5350 m depth: *Calyptogena phaseoliformis* habitat along the fault.

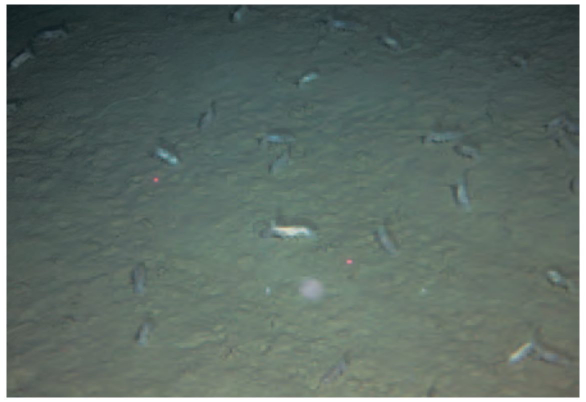
5351 m depth: A fissure about 1 m wide and 1 m deep continues for 80 m or more north to south. This fissure was not seen in a submersible survey of the same site in 2006. We think the fissure was caused by the Tohoku Earthquake.



5348 m depth: A bacterial mat extends in a line about 2 m long. Seawater containing methane is probably seeping from a fault below. In the water just above there is a high concentration of hydrogen sulfide. These bacteria produce hydrogen sulfide from methane and sulfates; it is likely that bacteria that use hydrogen sulfide as an energy source are also present. The lower picture is a magnified view of the bacterial mat, which has a gelatinous form.



5341 m depth: A bacterial mat covering an area about 20 m square.



5350 m depth: A dense aggregation of sea cucumbers (Elpidiidae). In the 2006 submersible survey, there were many sea anemones but no sea cucumbers were found.

A M9.0 megathrust earthquake would obviously cause great disruption under the sea as well as on the land, and would affect deep-sea ecosystems. However, there have been very few studies of the effects of earthquakes on ecosystems. In order to find out what effect the earthquake had under the sea, particularly on ecosystems, we planned a manned survey using *Shinkai 6500*.

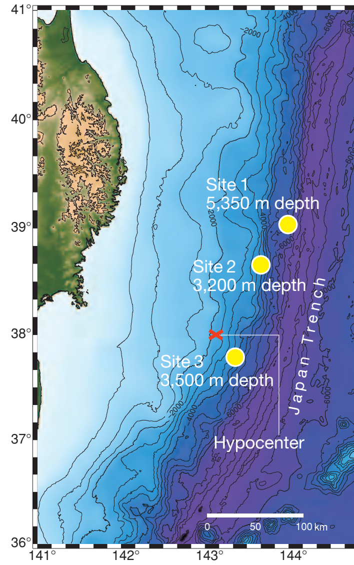
In June 2011, we conducted a preliminary study using Deep Tow, the deep ocean floor survey system carried by the *Yokosuka*. The Deep Tow camera showed sights that were not seen before the earthquake, such as colonies of sea cucumbers and discoloration of the seafloor. Taking the results of this preliminary survey into account, we selected three sites for observation with *Shinkai 6500*.

From July 30 to August 14, 2011, *Shinkai 6500* carried out a manned survey. The first thing that drew the attention of the crew when they reached the ocean bottom was a fissure running along the seafloor. This site, Site 1, had been surveyed by submersible in 2006. There was no fissure in 2006, so we think this fissure was probably caused by the Tohoku Earthquake.

White discolorations could be seen here and there on the seafloor, forming lines in some places and spreading over wide areas in others. These are bacterial mats, in which huge quantities of bacteria are growing. The linear bacterial mats have probably formed where there are faults below, from which seawater containing methane is seeping. We think that bacteria that use methane as an energy source are accumulating and producing hydrogen sulfide. Then bacteria that use the hydrogen sulfide grow in large quantities and thus form the bacterial mats. It is usual to see chemosynthetic communities in methane seepage areas, but there were no mega-benthic organisms such as white clams *Calyptogena phaseoliformis* at the bacterial mats.

Groups of sea cucumbers were seen. It is likely that sediment containing organic matter was stirred up by turbulent currents, causing the seafloor to became abundant with organic matter, and that sea cucumbers, feeding on the organic matter, appeared in large numbers for a limited period.

It is very likely that these changes were caused by the earthquake. Periodic surveys will be needed to follow changes in the future. As time passes, it may be that large organisms such as white giants clams will appear around the bacterial mats in methane seepage areas to form colonies of chemosynthetic organisms. Alternatively, the seafloor may return to the conditions before the earthquake. *Shinkai 6500* left markers for long-term monitoring on the seafloor. Surveys will continue in the future, and we will follow the processes of recovery and renewal of the deep sea ecosystems affected by the earthquake.

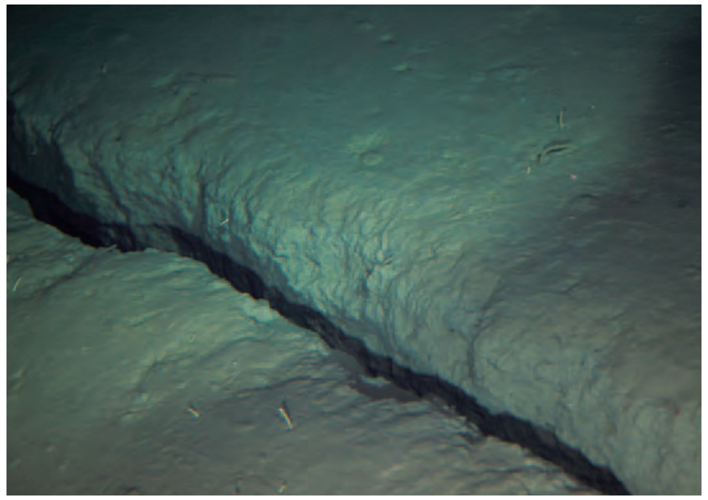


Sites of surveys by *Shinkai 6500*

Site 2

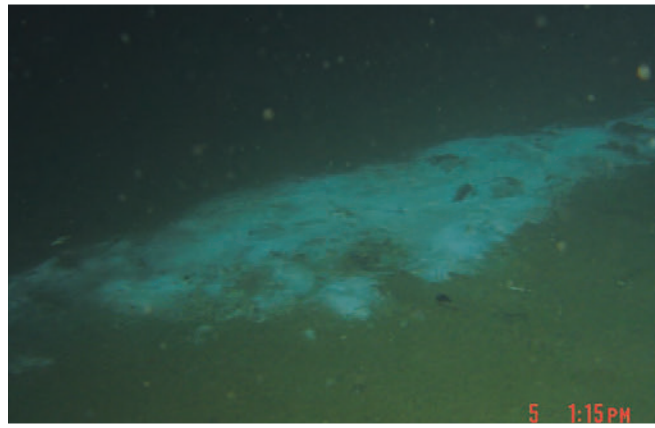
3200 m depth: There are no faults here but many bottom-dwelling organisms have been seen in previous surveys.

3218 m depth: A fissure about 20 cm wide continues for tens of meters in a north–south direction. The bottom of the fissure was too deep for the depth to be ascertained.



Site 3

3500 m depth: Changes in color of the seafloor were seen in the preliminary survey.



3551 m depth: A bacterial mat spreading 2–3 m in width and 5–6 m in length.

A sea anemone. About half of the sea anemones observed at site 3 were detached from the seafloor, which is a very unusual situation for sea anemones.

Disturbance of deep-sea environments induced by the M9.0 Tohoku Earthquake

Tectonic events such as earthquakes often trigger the typical environmental disturbances that include sudden outflows as well as cessations and changes in the chemical composition of groundwater and hot springs. In past, disturbance in deep-sea environment after a M5 level earthquake swarm was detected as the turbulent diffusion of sediments and a manganese concentration anomaly in a seafloor observatory. To describe the immediate and existing conditions in the deep ocean following the M9.0 earthquake and its aftershocks is thus a priority objective of multidisciplinary science and a basis for the socially necessary restoration of the marine ecosystem and fisheries in Japan.

To this end, oceanographic investigation were conducted by R/V *Mirai* on April 15 (36 days after the Tohoku Earthquake) and R/V *Yokosuka* on May 20 (70 days after) and June 17 (98 days after)*. Vertical hydrocasts of the CTD-CMS system (Conductivity Temperature Depth profiler with Carousel Multiple Sampling system) with a light transmission meter were conducted at four sites along a line from the hypocentral region to the Japan Trench. Along with in-situ monitoring of seawater turbidity (cloudiness due to seafloor sediments being stirred up), deep-sea water were sampled for analyzing chemical and microbial characteristics.

Anomalously cloudy condition was found in deep-sea environment at all the sites on April. The levels and extent of turbidity were greater closer to the bottom in vertical and the trench axis in horizontal. In order to directly see what was going on in the deep-sea environment, so on July 12 we lowered a deep sea camera system lander to the seafloor at the trench axis and on the seaward slope. We observed that the turbidity was severe 35 m from the seafloor at the trench axis and 20 m from the seafloor on the seaward slope. Even four months after the M9.0 shock, deep-sea water was still turbid. When a core of sediment collected by the lander was studied, a number of completely new layers were seen. This indicates that, while turbidity caused by tremors and landslides in the earthquake of March 11 had not continued for that long, the sediment would have repeatedly settled and been disturbed by aftershocks.

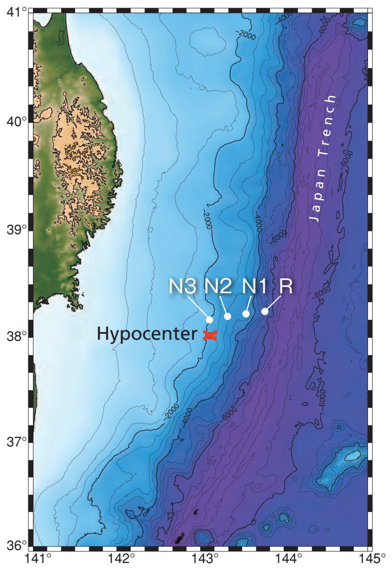
The chemical analyses of the samples revealed anomalously abundant manganese and methane in deep-sea water. Because manganese and methane are known to be abundant in seafloor sediments, it seems likely that the manganese and methane were stirred up at first. However, stable carbon isotope ratios of the methane indicated another distinguishable methane source than sedimentary one at the sites located on normal faults. Comparison of stable isotope ratios between the seawater methane and subseafloor methane, previously observed by drilling project, suggests that the methane would be derived from depths greater than 1,000 m below the seafloor. Geologic and chemical characteristics likely demonstrate that the deep subseafloor-derived methane would seep into the deep-sea water through the faults by earthquake-induced fluid pumping.

Along with the increases of chemical components, density of microorganisms had also increased to about three times usual levels, whereas the density immediately decreased to usual levels in 70 days and 98 days after the earthquake. Microbial community in the deep-sea water was analyzed by the 16S rRNA gene phylotype composition, and the increased microbes in 36 days after the event had two origins: (i) indigenous benthic microbial components that inhabited the shallow sediments before the earthquakes and (ii) fresh planktonic components that dominated the microbial communities by responding to the earthquake-induced influxes of reduced energy sources in the deep-sea water.

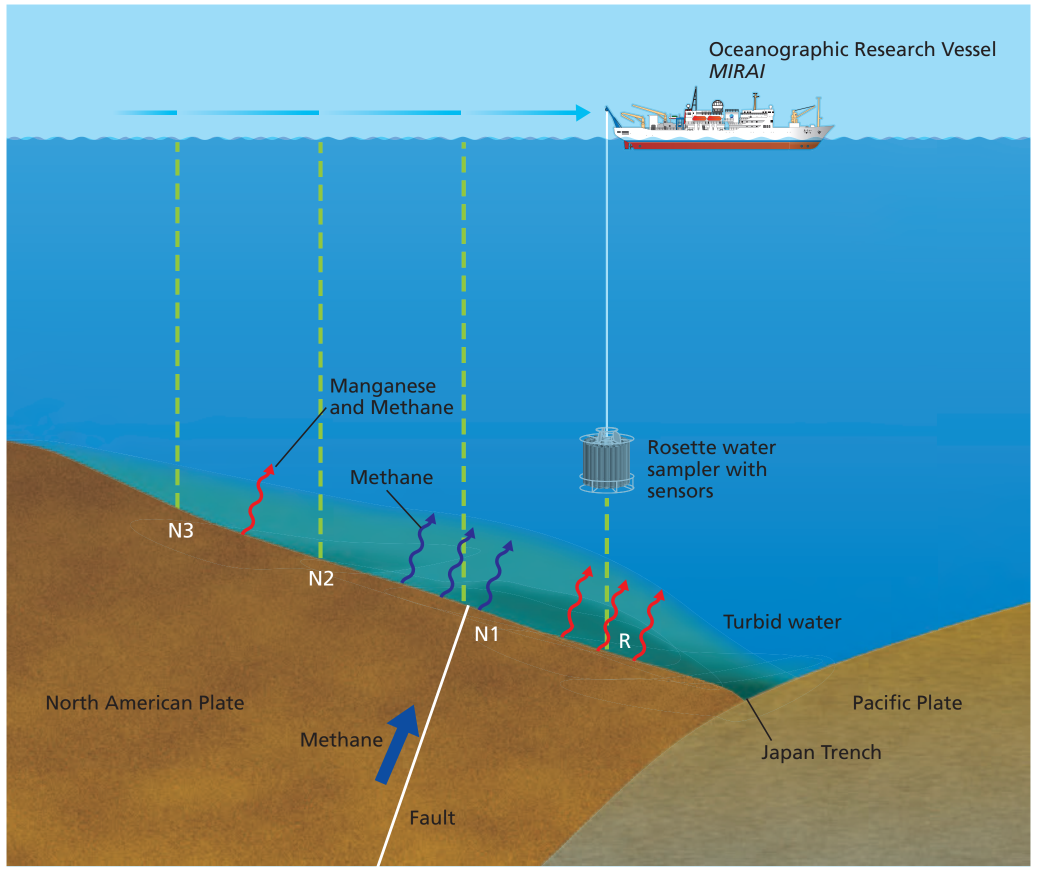
This is the first case to together detect the changes in the chemical environment and microorganisms after the earthquake. If the first cruise had not been carried out as soon as 36 days after the earthquake, the changes might not have been detected. Continuous investigations in the future will be necessary to find out how long it will take for the turbidity of the seawater, the levels of chemical anomalies, and the numbers and structure of microorganisms to return to the conditions before the earthquake, or indeed whether conditions will be different from before the earthquake.

A current focus of biogeoscience field is the source of the methane derived from deep subseafloor environment. It is known that molecular hydrogen is generated when a fault slips, and the experiment by JAMSTEC scientists demonstrated a correlation between amounts of molecular hydrogen generation and energy released from fault slipping. From the result, large amount of molecular hydrogen to have been produced by the M9.0 megathrust earthquake is expected. Because molecular hydrogen is an energy source to produce methane for subseafloor microbial ecosystem, the methane we detected may have been produced by linkage between earthquake and subseafloor ecosystem.

It seems that while the earthquake disrupted ecosystems, it may also nurture life. If samples can be retrieved from faults and hydrogen produced by earthquakes and microorganisms that use hydrogen as an energy source can be found, the existence of an "earthquake biosphere" can be demonstrated. As well as uncovering the mechanism of the earthquake, the drilling by *Chikyu* will help to test this new proposition.



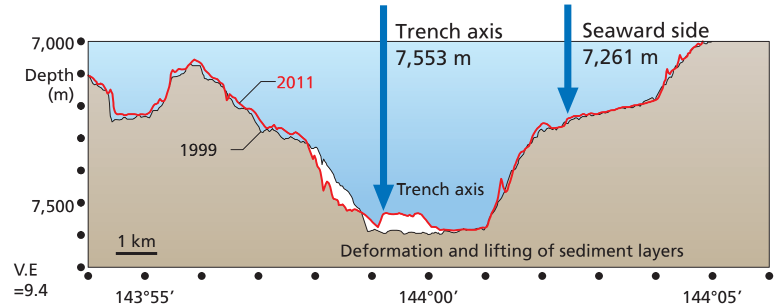
Study area
Hydrocast was conducted at four sites (N3, N2, N1 and R) on a line from the hypocentral region to the Japan Trench.



Schematic illustration of the results A CTD-CMS was casted from the R/V *Mirai* for observing deep-sea environment. Light transmission anomaly was found near the seafloor at all the sites. At the site close to the trench axis, turbid water was detected up to 1500 m altitude from the seafloor. High concentrations of manganese and methane were detected in the seawater. While they were derived partly from the seafloor sediment by earthquake movements and landslides, deep subseafloor methane upwelling through the normal fault would be also contributed.

The lander deployment
The lander can be submerged to a water depth of 11,000 m. It is equipped with a deep sea camera that can continuously record its surroundings for seven hours or more while descending and after landing. It is also equipped with three bottom samplers that can collect sediments from the top 50 cm of the seafloor.

Sites of surveys by the lander



*Kawagucci, S., Y. T-Yoshida, T. Noguchi, M. C. Honda, H. Uchida, H. Ishibashi, F. Nakagawa, U. Tsunogai, K. Okamura, Y. Takaki, T. Nunoura, J. Miyazaki, M. Hirai, W. Lin, H. Kitazato, and K. Takai, Disturbance of deep- sea environments induced by the M9.0 Tohoku Earthquake, Scientific Reports, 2,270,doi:10.1038/srep00270, 2012.
URL http://www.nature.com/srep/2012/120216/srep00270/full/srep00270.html

How Much and How Far has Radioactive Material Spread from the Fukushima Daiichi Nuclear Power Plant? Answering these Questions with Ocean Monitoring and Simulations

As a result of the earthquake and tsunami, there was an accident at the Fukushima Daiichi Nuclear Power Plant (FNPP), and radioactive materials including cesium, iodine and strontium were released. On March 22, 2011, Ministry of Education, Culture, Sports, Science & Technology in Japan (MEXT) announced an ocean monitoring plan for ocean areas off the coast of Fukushima Prefecture (outside a radius of 30 km from FNPP). At the ministry's request, JAMSTEC dispatched the *Hakuho Maru* to the Fukushima coast on the same day. Subsequently, the *Mirai*, *Kairei*, *Yokosuka* and *Natsushima* also took part in this ocean monitoring survey.

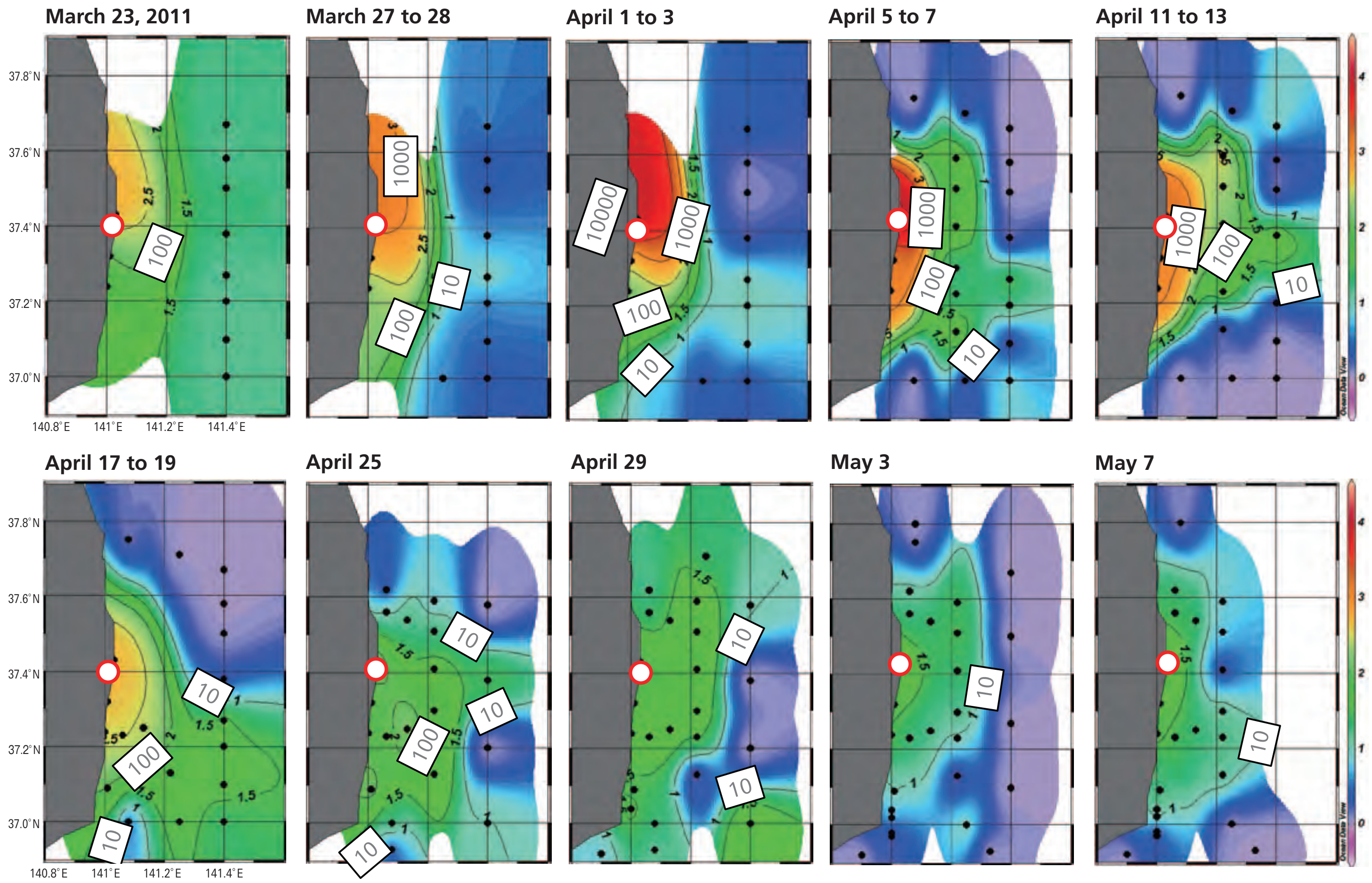
When a ship reaches a monitoring site, it first measures radiation levels in the atmosphere. Then, eolian dust (aerosol) is captured, sea water is collected, and seafloor sediment is sampled. The following day, these samples are delivered to Hitachinaka port, and levels of radioactivity are measured by institutions such as the Japan Atomic Energy Agency. The results are published on the ministry's website.

Cesium 137 is a particularly important monitoring subject. Cesium 137 stays in the environment for a relatively long time, with a half life of 30.1 years. There is concern that it may dissolve in sea water and accumulate in marine organisms through the food web. Concentrations of cesium 137 in the surface seawater around Japan before the FNPP accident were around 0.001 Bq/L (Becquerels per liter). In contrast, in mid-April after the accident, maximum concentration of 186 Bq/L was measured off FNPP. This is lower than the government's provisional standard for drinking water, 10 Bq/L, but is over 100,000 times higher than before the accident. The level has gradually decreased since then and was below the measurement threshold of 9 Bq/L at all monitoring sites by the end of September, 2011. Examining how the levels of cesium 137 have changed over time, we have found that while spreading north and south along the Fukushima coast, it has been spread east into the North Pacific by mesoscale eddies and the Kuroshio extension.

In addition to the ocean monitoring at the request of MEXT and the Marine Ecology Research Institute, JAMSTEC has been surveying the diffusion of cesium 137 in the North Pacific. As well as seawater, zooplankton and suspended particles in the seawater have been collected and their radiation levels measured. From the results at a measurement site 950 km from the power plant (S1), and another measurement site 1,900 km from the power plant (K2), we found that cesium 137 from FNPP was present in the seawater, zooplankton and suspended matter collected one month after the accident. Cesium 137 can be dispersed through the air, and seems to have spread over a wide area of the western North Pacific in a short time. The radiation levels are far below the government's provisional standards for meat, fish, etc. (100 Bq/kg), but are over 100 times what they were before the accident.

We have carried out simulations of the diffusion of radioactive material over a large area of the North Pacific, to understand when, where and at what levels the radioactive material has been spread and will spread. We ran simulations using the Japan Coastal Ocean Predictability Experiment (JCOPE) system for these purposes. JCOPE improves prediction accuracy by using data assimilation, a method for incorporating the latest measurement data into the system.

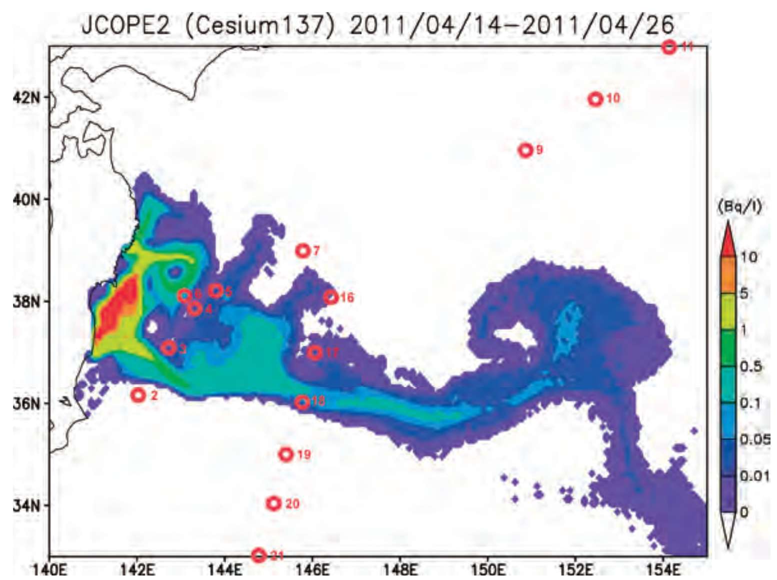
What happens to the radioactive material is of interest not only to Japan but to the whole world. We have a duty to carry out these ocean surveys and simulations and publish the results.



Changes over time of cesium 137 concentrations in surface seawater obtained by ocean monitoring

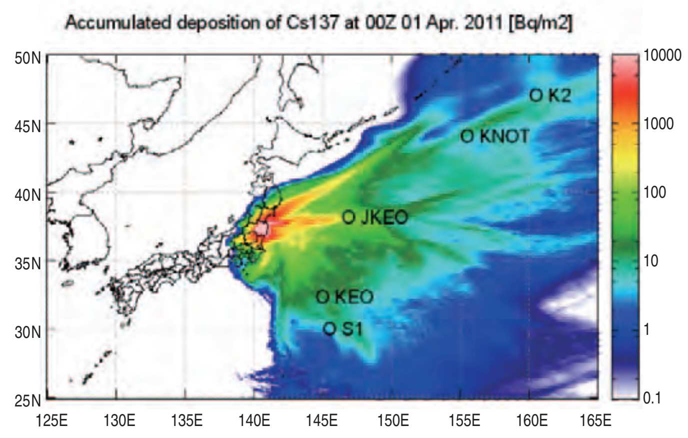
The units are Bq/L, and the contour lines show levels on a logarithmic scale. The red outline circle is the position of FNPP. The cesium 137 spread north and south along the coast, and then spread offshore (based on data from MEXT).

Simulation of the spread of water contaminated with radioactive material
After spreading north and south along the coast, the radioactive material released into the ocean from FNPP was carried offshore by a complicated current system. Radioactive material taken up by the Kuroshio extension was quickly carried eastward and diluted. After four to five months, the radioactive material had reached the area of the international date line, though the concentrations were very low. The relatively high concentrations of cesium 137 measured off the Sanriku coast were well reproduced by the simulation.



(Honda et al., Geochemical Journal, 2012)

Simulation of the spread of radioactive material through the air
The measured spread of radioactive material over a large area of the western North Pacific in only a month cannot be explained by the simulation of the diffusion of radioactive material directly discharged into the ocean (left). However, the measurements can be explained by adding a simulation of fallout of contaminated aerosol to the simulation of dispersion of contaminated water.



(Honda et al., Geochemical Journal, 2012)

Ocean monitoring of radioactive material

When the ship reaches a monitoring site, airborne radiation dose rate are measured on the deck.

Water sampling operations. The sampler is lowered by crane and collects seawater. An apparatus that captures aerosol is mounted on the tripod at the bottom-left of the picture.

Transferring the collected seawater to a 20-liter container (the transparent plastic container in the yellow box at the middle of the picture). The person in the foreground is an observer from the International Atomic Energy Agency (IAEA).

Recovering Rock Samples from the Plate Boundary Fault below the Seafloor of the Japan Trench

On May 21, 2012, many people in Japan were looking up at the sky, watching an annular eclipse of the sun. Meanwhile, the scientific deep sea drilling vessel *Chikyu* was above the Japan Trench, about 200 km offshore of, Miyagi Prefecture. It was to be an exciting day for Research Expedition 343 of the Integrated Ocean Drilling Program, conducting the Japan Trench Fast Drilling Project to investigate the area of the Tohoku Earthquake. The expedition had begun on April 1 and would finish a few days after the eclipse.

In the 2011 Tohoku earthquake, the seafloor moved about 50 m east-southeast and 7–10 m upward. The large seafloor displacements (largest ever measured for an earthquake) was the the result of movement a fault that extended from about 50 km depth to the surface near the trench axis. Usually in such earthquakes the deeper portion of the fault slips, but the large movement on the shallow portion was unexpected. This large slip on the shallow part of the fault was largely responsible for the tsunami that devastated much of the northeast coast of Honshu. To understand this very large slip on the shallow portion of the subduction zone, an international science team made a plan to study the characteristics of the fault zone by drilling to the fault zone. This expedition had two primary missions: to place thermometers in boreholes to measure temperatures; and to recover rock samples from the fault zone.

During an earthquake there is heat produced because of the friction between the two sides of the slipping fault surface. By measuring the temperature near the fault soon after an earthquake, we can determine the level of friction and stress that control the rupture process. Also, material properties of the fault zone and surrounding area can be directly studied by recovering rock samples. By analyzing the temperature data along with the rock samples, we can learn what happened on the fault below the seafloor during the Tohoku Earthquake. This was the objective of the scientific expedition.

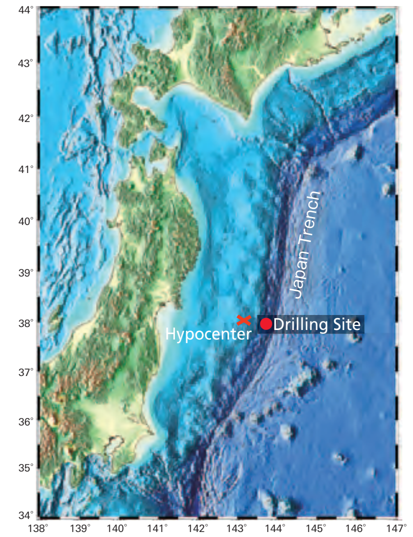
During the expedition, *Chikyu* first conducted "logging-while-drilling" to locate the fault. Physical measurement sensors were installed near the tip of the drill pipe and physical data in the borehole was acquired simultaneously with the drilling. This drilling reached 850.5 m below the sea floor, under 6889.5 m of water, a total drillpipe length of 7740 m. This was a new world record, breaking the 7049.5 m (7034 m water depth and 15.5 m under the seabed) drilled into the Challenger Deep of the Mariana Trench by the *Glomar Challenger* in 1978.

On May 13, coring to recover rock samples finally began. From previous seismic surveys and the logging-while-drilling data, the science team estimated that the plate boundary fault was close to 820 m below the seafloor. Scientists had been anxiously waiting for the samples from this depth, and these important cores were finally brought up to *Chikyu* on the evening of May 21, just a few days before the scheduled end of the expedition.

Scientists and drilling engineers excitedly gathered as the cores were brought onboard. "Here it is!", "Why does it look like that?", "Fascinating!" were the comments heard, as scientists were wondering if it actually was the fault. One structural geology expert closely examined the rocks and proclaimed "Definitely. This is the fault." There was a spontaneous round of applause.

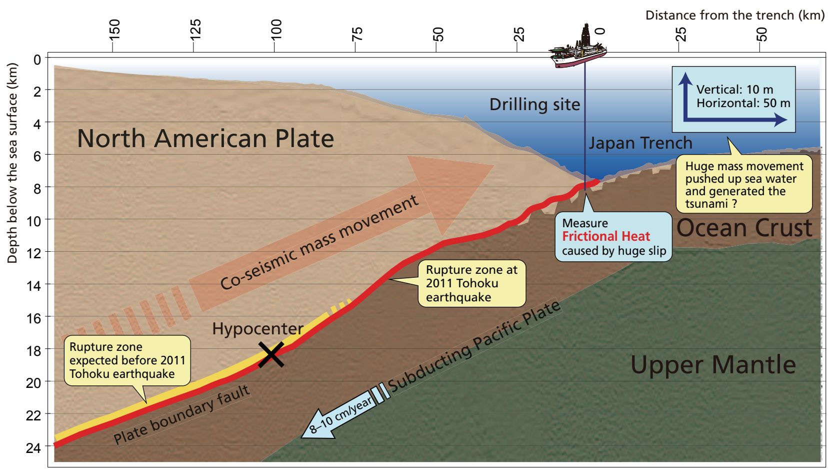
Rocks from a plate boundary fault of a subduction earthquake have never before been quickly sampled within about a year after the event; this is a world first. However, there are many faults at a plate boundary, so detailed analysis will be necessary to identify the specific fault that caused the Tohoku Earthquake and the tsunami. The installation of thermometers in boreholes had to be postponed because of various technical problems, such as failure of the underwater camera system. However, during a return trip to the site in July, these instruments were successfully deployed. The fault that slipped in the earthquake should still retain the frictional heat and measurement of a small thermal signal is expected. Data from the borehole thermometers is expected to help identify the fault and provide information about the important friction level.

Sample of the plate boundary fault recovered from the Japan Trench (image provided by JAMSTEC/IODP)



The drilling site
The drilling was carried out about 200 km east of the Oshika Peninsula, Miyagi.

Sample of the plate boundary fault recovered from the Japan Trench (image provided by JAMSTEC/IODP)



Conceptual image of sub-seafloor structure at the drilling site
Chikyu drilled down to the plate boundary fault, about 850.5 m below the seafloor under a water depth of 6889.5 m. Plate boundary fault rock samples were recovered from 648–844.5 m below the seafloor.

The Hidden Details of a Magnitude 9 Megathrust Earthquake: Tracking Changes after the Earthquake, Probing into the Past, and Using the Findings for the Future

A sunset photographed from *Chikyu* during the drilling to the plate boundary fault that was the source of the Tohoku Earthquake (image provided by JAMSTEC/IODP)

■Launching the Tohoku marine science project

JAMSTEC is currently building a new research vessel. This vessel will primarily be used for the Tohoku marine science project launched in January 2012. The Tohoku marine science project will be led by Tohoku University, Atmospheric and Ocean Research Institute of the University of Tokyo, and JAMSTEC, with participation by other Japanese universities, research institutes, private businesses, etc.; its aims are to identify the effects of the Tohoku Earthquake and Tsunami on ocean ecosystems along the coast, understand the mechanisms of change and, with scientific data, contribute to the recovery of fisheries and the establishment of new businesses.

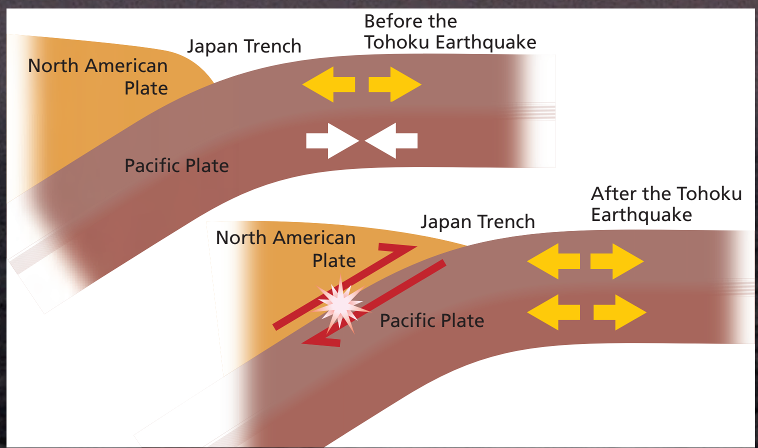
■Changes in stress fields inside the Pacific Plate

Even while recovery is progressing, everyone is concerned about the possibility of another large earthquake.

At 3:25 p.m. on March 11, 2011, about 40 minutes after the Tohoku Earthquake, there was a magnitude 7.5 aftershock. The hypocenter was 11 km deep in the Pacific Plate on the east side of the Japan Trench. Vigorous aftershock activity continued for some time on the east side of the Japan Trench. In late April 2011, JAMSTEC used the R/V *Kairei* to install 20 ocean bottom seismographs on the east side of the Japan Trench, and started aftershock observations. In early July 2011, the R/V *Yokosuka* recovered the ocean bottom seismographs and we analyzed the recorded seismic waves. From the analysis of the seismic waves, not only the hypocenter location but what types of forces were acting on faults and causing earthquakes can be ascertained. The results of the analysis showed that the hypocenters of the earthquakes were distributed around 40 km deep in the Pacific Plate. In a detailed analysis of 50 quakes, all were found to be normal fault type earthquakes caused by extension forces.

What was the situation before the Tohoku earthquake? According to the results of ocean bottom seismograph measurements previously conducted by Tohoku University and others, extension forces were acting up to about 20 km below the seafloor and compression forces were acting deeper down. The actions of these forces and stress fields indicated bending in accordance with the subduction of the Pacific plate. After the earthquake, the stress fields in the deeper regions changed from compression fields pushing the rocks together to extension fields pulling the rocks apart. This is the first time ever that changes in stress fields within a plate due to a subduction zone earthquake have been observed on the seaward side of a trench.

The situation in which extensional fields reached down to around 40 km deep within the Pacific Plate means that faults are more likely to slip all at once from a deep region to a shallow region, and thus more likely to cause a large earthquake. When the hypocenter of an earthquake is shallow, a large tsunami may occur. The Showa-Sanriku earthquake of 1933 also happened within the Pacific Plate on the east side of the Japan Trench. With a magnitude of 8.1, it caused a large tsunami and a great amount of damage. In 1896, 37 years before that, the Meiji-Sanriku earthquake had a magnitude of 8.2 with its hypocenter at the Japan Trench. It is thought that the stress fields in the Pacific Plate on the east side of the Japan Trench were changed by the Meiji-Sanriku earthquake, and that this may have been the cause of the Showa-Sanriku earthquake. If that is the case, it is possible that another large earthquake causing a tsunami will occur on the east side of the Japan Trench in the near future.



The change in stress fields within the Pacific Plate: before and after the Tohoku Earthquake
Before the earthquake, shallower parts of the Pacific plate were being pulled apart by an extension field and deeper parts were being pushed together by a compression field. Since the earthquake, the extension field reaches to a depth near 40 km. A large normal fault earthquake can readily occur under this condition.

■Continuing research into the Tohoku Earthquake

To find out if that is the case, we will need to continue seismic observations at the seafloor to monitor the changes in stress fields within the Pacific Plate. We will not be able to say that research into the Tohoku earthquake has been completed; we will have to continue. Against this background, a five-years project "Investigations of earthquakes and tsunamis off the Tohuku Pacific coast" was launched in 2011. The participants are Earthquake Research Institute of the University of Tokyo, Hokkaido University, Tohoku University, Chiba University, the National Institute of Advanced Industrial Science and Technology, and JAMSTEC. Areas that JAMSTEC will be responsible include surveys of sub-seafloor structure, surveys of seafloor topography, and seafloor seismic observations on the east side of the Japan Trench.

The sub-seafloor structure survey will be carried out at a high resolution along closely spaced survey tracks over the whole area of the Japan Trench. The main aim is to identify traces of megathrust earthquakes like the deformations of the sub-seafloor structure discovered in the survey after the Tohoku Earthquake. This will allow us to understand whether the Tohoku Earthquake was an unusual event or whether similar events have been repeated at different places along the Japan Trench. However, a sub-seafloor structure survey by itself will not show when changes in the sub-seafloor structure occurred. Therefore, we are planning to recover sediments from the seafloor with a piston corer and identify the dates of changes. From these measurements, we hope to draw up a timeline of large subduction zone earthquakes and tsunamis, identify their mechanisms, and help to mitigate damage from earthquakes that happen in the future.

■Preparing for a megathrust earthquake in the Nankai Trough

Past survey data has been very useful in our studies of the Tohoku Earthquake. We have been able to find the changes caused by the earthquake by comparisons with data from before the earthquake. This reaffirms the importance of collecting basic data, even though it may not be immediately useful. It is also important not to leave areas unobserved. While the Japan Trench off Tohoku has been the focus of attention, it will also be necessary to perform surveys and measurements of the Japan Trench off the Boso Peninsula and of the Okinawa Trough.

Then there is the Nankai Trough. The Philippine Sea Plate is subducting below the Eurasian Plate, on which western Japan sits, at the Nankai Trough. The Nankai Trough has repeatedly experienced earthquakes of magnitude 8 and above at 100 to 200 year intervals. Looking at previous time gaps between earthquakes, the next earthquake that happens here may be a megathrust earthquake that links possible earthquakes including a "Tokai earthquake" with a hypocenter at the Suruga Trough, a "Tonankai earthquake" with a hypocenter at the Nankai Trough in the sea off the Tokai region to off Cape Shionomisaki in the Izu Peninsula, or a "Nankai earthquake" with a hypocenter at the Nankai Trough between Cape Shionomisaki and Cape Muroto in Shikoku. Further west, the possibility has recently emerged of linking to a "Hyuga-Nada earthquake" with a hypocenter in the Hyuga-Nada Sea off Kyushu. In this case, a magnitude of 9.0, the same as the Tohoku Earthquake, has been predicted.

At JAMSTEC, we are continuing drilling in the Nankai Trough with D/V *Chikyu*, with the aim of discovering the mechanisms of earthquakes in the Nankai Trough. We have constructed the Dense Ocean Floor Network for Earthquakes and Tsunamis (DONET) system in the Kumano-Nada Sea off Kii Peninsula, which is a source region of Tonankai earthquakes, and put this system into operation in August 2011. Data from closely spaced ocean bottom seismographs installed on the seafloor and tsunami gauges is transmitted to the land in real time by cables and used for the Earthquake Early Warning. We are proceeding with preparations for the construction of a second stage of DONET off the Kii Channel, which is expected to be the source region of a Nankai earthquake. BE

獨立行政法人
海洋研究開發機構

http://www.jamstec.go.jp/

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Yokosuka Headquarters
Public Relations Division
2-15, Natsushima-cho, Yokosuka-city, Kanagawa, 237-0061, Japan
PHONE: +81-46-867-9070
FAX: +81-46-867-9055
Email: www-admin@jamstec.go.jp

Editing **Photon Create Inc,.** Design **Design Convivia Co., Ltd.**